this theory,[2] but the clearest proof would seem to be the observation of the simultaneous ejection of a proton and a neutron in the photodisintegration of a complex element. We have recently observed coincident protons and neutrons from lithium irradiated with 265-Mev bremsstrahlung from the University of Illinois betatron.

In our experiment a proton counter consisting of a series of five organic scintillators was set at 76.5° to the x-ray beam. Pulse heights photographed from an oscillograph in three of the organic scintillators allowed an almost unambiguous identification of the particle and its energy. Protons in the energy range 65 Mev to about 200 Mev were observed in the same betatron run. When this counter was run by itself, electrons, mesons, meson stars, and protons were all clearly distinguished. This counter is more adequately described in the accompanying letter on the photodisintegration of deuterium.

In order to observe coincident protons and neutrons a counter 4 inches in diameter by 10 inches long filled with terphenyl in phenylcyclohexane was placed behind 2 inches of lead on the side of the beam opposite the proton counter. A coincidence between this counter and the proton telescope triggered the sweep of the oscillograph used for photographing the pulse heights. The pulse height distribution in the proton telescope clearly indicated that only protons were in coincidence with neutrons on the other side of the beam.

A further check on the two-body nature of such interactions was made by swinging the neutron counter in angle. Figure 1 shows the number of coincidences from a lithium target as a function of the neutron counter angle. A definite angular correlation is observed. The angular correlation from deuterium is shown for comparison. The equality of the peak angles gives striking confirmation of the two-body nature of the interaction. The broadening of the lithium curve is about what would be expected from the internal momentum distribution of the "pseudodeuteron" in the nucleus.

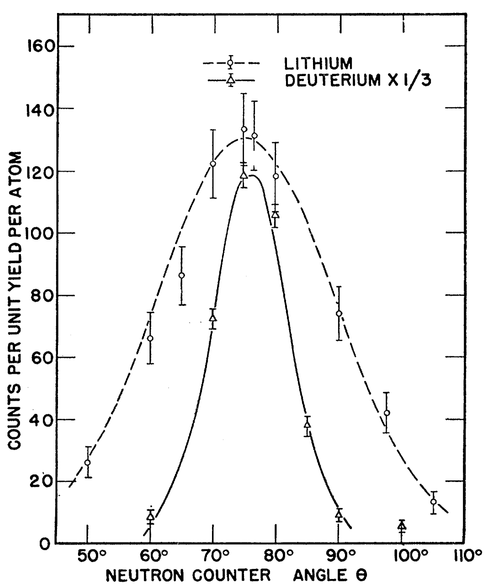


FIG. 1. Neutron-proton coincidences as a function of the angle of the neutron counter. The proton counter is fixed at 76.5°. The lithium ordinate is in most cases the actual number of counts observed. The deuterium curve has been normalized for number of atoms in the beam and reduced by a factor of three to facilitate comparison.

In a supplementary experiment with A. O. Hanson and T. Yamagata described in an accompanying letter, the liquid deuterium target was used to measure the efficiency of our neutron counter as 6.8 percent. We can then estimate that 53 percent of all photoprotons from lithium have a correlated neutron. If the probability of subsequent interactions in the nucleus is taken into account, the possibility remains that all photoprotons in this energy range are produced in such a two-body process.

We have observed this effect qualitatively in beryllium, carbon, boron, nitrogen, and oxygen targets.

The data presented in this letter are at best preliminary, and quantitative conclusions are subject to considerable uncertainty. However, the qualitative existence of correlated protons and neutrons in the high-energy photoeffect leaves little doubt of the basic correctness of the "pseudodeuteron" model for at least a large fraction of the interactions.

* This work was supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] J. S. Levinger, Phys. Rev. 84, 43 (1951).
[2] J. W. Weil and B. D. McDaniel, Phys. Rev. 92, 391 (1953). See this paper for other references.

## Photodisintegration of Deuterium by 265-Mev Bremsstrahlung

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WE have measured the differential cross section of the photodisintegration of deuterium at 45°, 75°, and 120° in laboratory coordinates.

Figure 1 shows the schematics of our experimental arrangement. The liquid deuterium target[1] was placed in the x-ray beam from the University of Illinois betatron. The proton counter telescope consisted of five organic scintillators. Two of them, viewed by 931-A phototubes, supplied pulses for a coincidence circuit which triggered the sweep of an oscilloscope. The other three crystals were viewed by 5819 phototubes. Their outputs were suitably delayed, put in a mixing and integrating circuit, and displayed on the oscilloscope. 35-mm photographs of the individual traces were later projected and the pulse heights measured.

In most cases, pulses from protons, mesons, and electrons are readily distinguishable, since particles differing

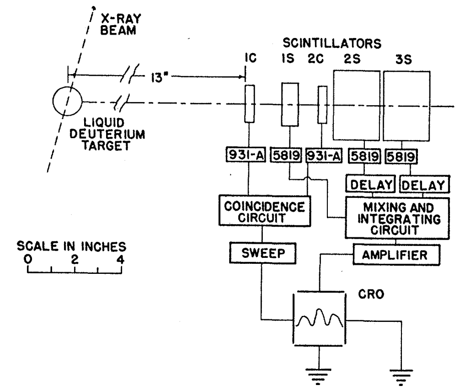


FIG. 1. Sketch showing size of scintillators in proton counter and block diagram of associated electronics.

in mass have different correlations between the three pulses recorded on the film. In Fig. 2, a typical plot of the pulse heights in $1-S$ *vs* those in $2-S$ is shown. It is seen that the points make three distinct groups. The outermost group is protons, whereas the middle and the innermost are mesons and electrons, respectively.

As can be seen in Fig. 2, protons with sufficient energy to pass through $2-S$ might be confused with lower energy protons or meson stars except for the third pulse. The plot of the second *vs* the third pulse heights shows a pattern similar to Fig. 1 and serves for the necessary identification.

The energy of a proton was determined by measurement of the height of the second or the third pulse, according as the proton stopped in the second crystal or entered the third one. The energy loss in these two crystals was calculated as a function of the initial photon energy, and taking into account the light output efficiency of the crystal[2] and nonlinearity of the chain amplifiers, a pulse height *vs* photon energy curve was established. For the calibration, the maximum energy losses in these crystals were assigned to the highest pulses. It was also possible to shift the energy scale by putting an aluminum absorber between the first two scintillators.

The number of protons found in a certain energy bin had to be corrected for scattering effects. Two attempts were made to account for the nuclear scattering. The first was to use the geometrical cross section as the nuclear scattering cross section. An isotropic angular distribution was assumed in the center-of-mass coordinates. The portion of protons which miss the $2-C$, $2-S$, or $3-S$ crystals (referring to Fig. 1) were calculated. This correction reaches a maximum value of 17.6 percent. Since the error due to nuclear scattering

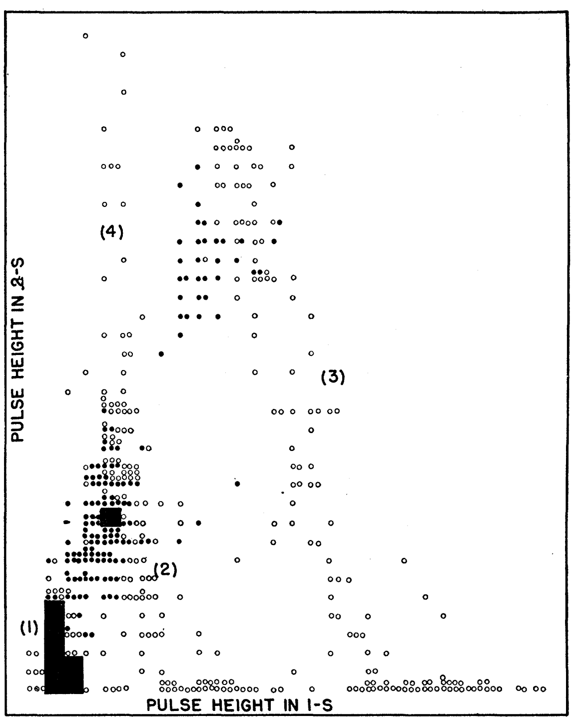


FIG. 2. Correlation of pulse heights in $1-S$ and $2-S$. Each point represents an event with pulse heights in $1-S$ and $2-S$ indicated by position on the chart. A solid circle indicates there is a pulse present in the last crystal $3-S$. Its height is not indicated. Electrons, mesons, and protons form distinct groups labeled 1, 2, and 3, respectively. Group 4 probably represents meson stars. Regions too dense to show individual events have been blackened in.

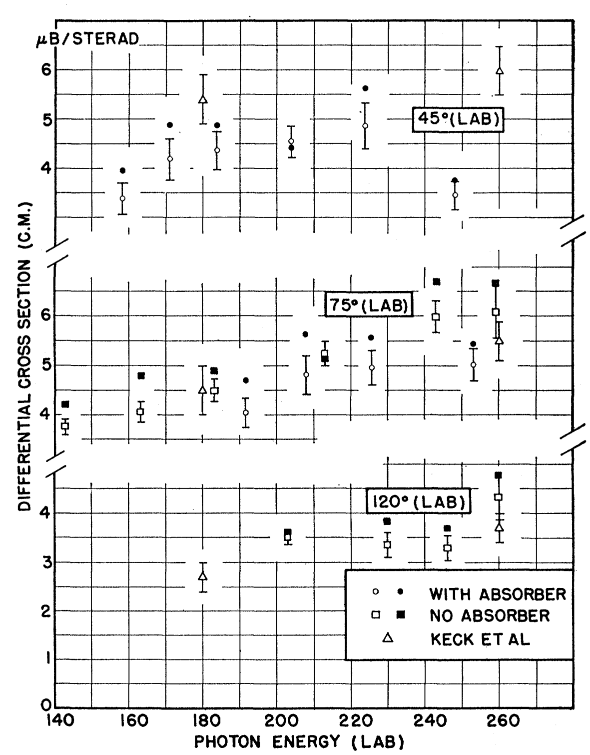


FIG. 3. Differential cross section of the photodisintegration of deuterium at 45°, 75°, and 120° in laboratory coordinates. Open points are corrected using geometrical cross sections. Solid points are corrected on a basis of neutron scattering cross sections.

is large, a second correction using the total cross section for neutron scattering as given by Taylor *et al.*,[3] was used, which represents an upper limit on the correction.[4] In this case, the maximum correction amounted to 28.3 percent. Coulomb scattering and multiple scattering effects were not corrected for, because they were found much smaller than the nuclear scattering effect.

Figure 3 shows graphs of our results. The open and the solid points correspond to the first and second type correction, respectively. The indicated standard deviations are due to the counting statistics only. They are in general consistent with the results of Keck *et al.*,[5] which are also plotted on the graphs. The values are not very consistent in the highest-energy bin. This is not surprising, since the scattering effects are the largest there, and also since the value there is very sensitive to the maximum energy of the bremsstrahlung.

[1] E. A. Whalin and R. A. Reitz, Rev. Sci. Instr. (to be published).
[2] J. B. Birks, Proc. Phys. Soc. (London) **A64**, 1814 (1951).
[3] A. E. Taylor and E. Wood, Phil. Mag. **44**, 95 (1953).
[4] H. de Carvalho found recently that nuclear scattering cross sections for protons and neutrons agreed well at high energies. [Cosmic-Ray Symposium at Purdue University, Indiana, May, 1954 (unpublished).]
[5] Keck, Littauer, O'Neill, Perry, and Woodward, Phys. Rev. **93**, 824 (1954).

# Neutrons in Coincidence with High-Energy Photoprotons*

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A GREAT deal of effort has been devoted at many laboratories to the study of high-energy protons ejected from various nuclei by approximately 300-Mev bremsstrahlung.[1] It was proposed by Levinger[2] that these photoprotons could be explained on the basis of the disintegration of a quasi-deuteron subunit in the nucleus. The proton energy spectra were in general qualitative agreement with the predictions of this model. However, the possibility existed that the agreement was fortuitous[1]; it was felt that it would be desirable to see if neutrons and protons were emitted simultaneously in high-energy photoproton reactions. The results of a preliminary experiment described below are that neutrons and protons are emitted simultaneously from nuclei and have the proper dynamical relationships. This result removes all doubts concerning the validity of the quasi-deuteron model for the photoproton ejection process.

A proton telescope consisting of three scintillators was employed with an energy spread of about 10 Mev at 135 Mev. In these measurements the proton detector was fixed at 45°. A neutron detector consisting of a cylinder of scintillating liquid 10 cm in diameter and 30 cm long was employed. The efficiency of the neutron detector had been previously determined to be 9 percent with the aid of neutrons from the Harvard cyclotron. Measurements were made of the number of coincidences between these two detectors as a function of the angle of the neutron counter. In these measurements the bremsstrahlung beam from the M.I.T. synchrotron was run at 325 Mev. As a check of the equipment the neutron-proton coincidences from the photodisintegration of deuterium were studied by a $D_2O - H_2O$ subtraction. Measurements were then made of the neutron-proton coincidences from carbon. The results of both of these measurements are shown in Fig. 1.

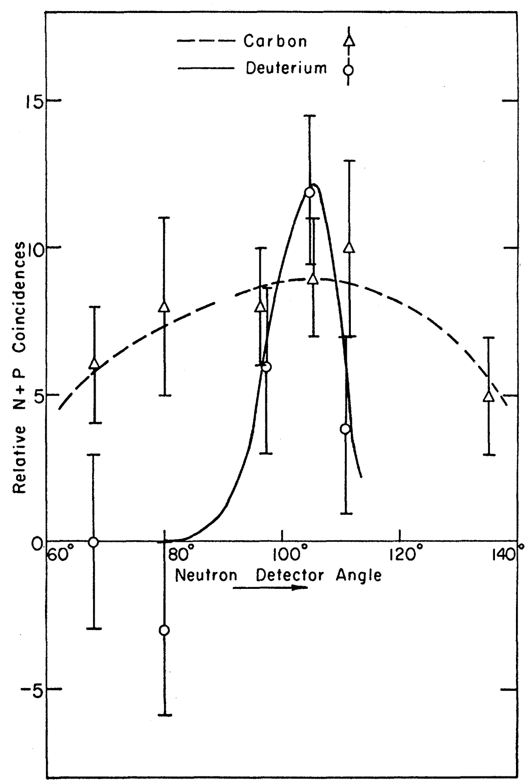


Fig. 1. Neutron-proton coincidences from carbon and deuterium as a function of the angle of the neutron counter. The coincidences are expressed in relative counts per atom per monitor unit.

Unfortunately, the mounting of the equipment did not permit a larger range of angles than that shown in the figure. The oxygen coincidences had the same angular distribution as those from carbon to within the statistics obtained. The accidental coincidence rate was measured and found to be negligible.

If one assumes that the neutrons are emitted in an angular cone around the angle predicted for the neutrons from deuterium and if one assumes that the angular distribution does not extend appreciably beyond the